arXiv:astro-ph/0110549v1 25 Oct 2001

# Spectroscopic Analysis of the DAB White Dwarf PG 1115+166: An Unresolved DA + DB Degenerate Binary

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## ABSTRACT

A spectroscopic analysis of the DAB white dwarf PG 1115+166 is presented. The observed hydrogen and helium line profiles are shown to be incompatible with model spectra calculated under the assumption of homogeneous or stratified chemical compositions. In contrast, an excellent fit to the optical spectrum of PG 1115+166 can be achieved if the object is interpreted as an unresolved double degenerate composed of a hydrogen-line DA star and a helium-line DB star. The atmospheric parameters obtained from the best fit are $T_{\rm eff} = 22,090$ K and $\log g = 8.12$ for the DA star, $T_{\rm eff} = 16,210$ K and $\log g = 8.19$ for the DB star. This binary interpretation is consistent with the results recently reported by Burleigh et al. that PG 1115+166 also exhibits radial velocity variations. The implications of this discovery with respect to the DAB spectral class are discussed.

*Subject headings:* stars: binaries, stars: individual (PG 1115+166), white dwarfs

## 1. Introduction

DAB stars are white dwarfs whose optical spectra are characterized by the simultaneous presence of strong hydrogen Balmer lines together with weaker neutral helium lines. To date, only a handful of these objects are known (see Burleigh et al. 2001, and references therein). DAB stars are particularly important objects as they are likely to provide the key to understanding the nature of the so-called "DB gap", a range in effective temperature between $T_{\rm eff} \sim 30,000$ and 45,000 K where no helium atmosphere white dwarf (DO or DB stars) has ever been identified (Liebert et al. 1986); the coolest DO star PG 1133+489 has an estimated temperature of $T_{\rm eff} = 46,000$ K (Dreizler & Werner 1997), while the hottest DB star PG 0112+104 is below $T_{\rm eff} = 31,500$ K (Beauchamp et al. 1999). The most widely accepted explanation for the presence of this gap is the existence of competing mechanisms that are affecting the atmospheric composition of white dwarfs as they evolve along the cooling sequence (see, e.g., Fontaine & Wesemael 1997). Hence it is believed that residual hydrogen present in the envelope of hot DO white dwarfs slowly diffuses towards the surface, building an atmosphere that is gradually enriched with hydrogen. By the time cooling DO stars have reached $T_{\rm eff} \sim 45,000$ K, they would all bear the signature of a hydrogen-rich atmosphere, a DA star. Such DA stars should have a thin hydrogen atmosphere in diffusive equilibrium on top of the helium envelope. At the red edge of the DB gap, convective dilution of this thin hydrogen atmosphere with the underlying convective helium envelope is then believed to turn $\sim 20\%$ of all DA stars near $T_{\rm eff} \sim 30,000$ K into DB white dwarfs. The identification of white dwarfs with hybrid spectra in these particular ranges of effective temperature has always been of significant interest since they may represent objects transitioning from one spectral type to another.

Recently, Burleigh et al. (2001) have reported the discovery of a new DAB white dwarf, PG 1115+166, as part of a survey aimed at identifying helium-rich objects crossing the DB gap. The authors have examined hot white dwarfs that went undetected by the ROSAT and EUVE surveys of the extreme ultraviolet sky. Effective temperatures and surface gravities for the objects in their sample had been supplied by us as part of another project aimed at redetermining the luminosity function of DA stars using $T_{\rm eff}$ and $\log g$ values obtained from detailed fits to the hydrogen lines (see, e.g., Bergeron et al. 1992). As such, the DAB nature of PG 1115+166 was already known to us back in 1996 from our own spectroscopic observations of the PG sample. The optical spectrum of PG 1115+166 had also been thoroughly analyzed using model atmospheres with homogeneous and stratified helium/hydrogen compositions. In this paper, we report the results of our findings. Interestingly enough, we show that the conclusions of Burleigh et al. (2001) that PG 1115+166 is probably a double degenerate binary composed a DA and a DB star is confirmed by our detailed analysis.

We first present our spectroscopic observations and model atmosphere calculations in §§ 1 and 2, respectively. The optical spectrum is then analyzed in detail in § 3 using using homogeneous, stratified, and composite model atmospheres. Our discussion of the results follows in § 4.

## 2. Spectroscopic Observations

Optical spectroscopy for PG 1115+166 has been obtained on 1996 May 20 using the Steward Observatory 2.3-m reflector telescope equipped with the Boller & Chivens spectrograph and a Loral CCD detector. The 4.5 arcsec slit together with the 600 l/mm grating in first order provided a spectral coverage of $\lambda\lambda$3200–5300 at an intermediate resolution of $\sim 6$ Å FWHM.

Our optical spectrum for PG 1115+166 is compared in Figure 1 with those of MCT 0453−2933 and MCT 0128−3846 taken from Wesemael et al. (1994). There is an obvious similarity between all three objects. The HeI $\lambda\lambda$4026 and 4471 absorption lines can be seen in all three spectra with about equal shape and strength. Weaker HeI features at $\lambda\lambda$4713, 4921, and 5015 are also observed in PG 1115+166 and MCT 0453−2933; these lines are much weaker but nevertheless present in the spectrum of MCT 0128−3846. The two MCT objects have been analyzed by Wesemael et al. (1994) and shown to be unresolved, composite systems consisting of a DA white dwarf together with a DB or DBA star.

## 3. Model Atmospheres and Synthetic Spectra

The mixed hydrogen and helium model atmospheres and synthetic spectra used in this analysis are described in Bergeron et al. (1994). These are calculated assuming either a homogeneous or a stratified chemical H/He composition. The homogeneous model atmospheres are similar to those described in Wesemael et al. (1980), while the stratified configurations have been calculated using the formalism discussed at length in Jordan & Koester (1986) and Vennes & Fontaine (1992). The homogeneous model grid covers a range of $T_{\rm eff} = 20,000$ (5000) $100,000$ K, $\log g = 6.5$ (0.5) 8.5, and $\log N({\rm He})/N({\rm H}) = -5.0$ (1.0) 0.0 (where the numbers in parentheses indicate the step value), as well as pure hydrogen models. Stratified models have been calculated for the same range of effective temperature and surface gravity, with $\log q_{\rm H} \equiv \log M_{\rm H}/M_\star = -17.0$ (0.5) $-$ 15.0 at $\log g = 8.0$. As discussed in Bergeron et al. (1994), the particular range of $\log q_{\rm H}$ used varies with $\log g$ as to yield synthetic spectra that look relatively similar with respect to the strength of the helium lines

in the $\log g - \log q_{\rm H}$ plane.

The synthetic spectra for the mixed H/He models have been calculated following Bergeron et al. (1991, see also Bergeron et al. 1992; Bergeron 1993), where the treatment of the hydrogen line profiles is described at length. The HeI lines have been treated as Voigt profiles with the Stark broadening parameters listed in Bergeron et al. (1994).

Our grid of model atmospheres and synthetic spectra for DB stars is described in Beauchamp et al. (1996). These include the improved Stark profiles of neutral helium of Beauchamp et al. (1997). The model atmospheres used here assume a pure helium composition and cover a range of $T_{\rm eff}$ = 10,000 (1000) 16,000 (2000) 30,000 K and $\log g$ = 7.0 (0.5) 9.0.

## 4. Model Atmosphere Analysis

Our fitting technique relies on the nonlinear least-squares method of Levenberg-Marquardt (Press et al. 1986), which is based on a steepest descent method. The model spectra (convolved with a Gaussian instrumental profile) and the optical spectrum of PG 1115+166 are first normalized to a continuum set to unity. The calculation of $\chi^2$ is then carried out in terms of these normalized line profiles only. All atmospheric parameters – $T_{\rm eff}$, $\log g$, $N({\rm He})/N({\rm H})$ or $\log q_{\rm H}$ – are considered free parameters. When fitting DA + DB model spectra, the total flux of the system is obtained from the sum of the monochromatic Eddington fluxes of the individual components, weighted by their respective radius. Those radii are obtained from the thin and thick hydrogen envelope evolutionary models with carbon/oxygen cores described in Bergeron et al. (2001).

Our best fits to the optical spectrum of PG 1115+166 using homogeneous, stratified, and composite DA+DB models are shown in Figure 2. The solution using homogeneous models, $T_{\rm eff} = 32,000$ K, $\log g = 7.95$, and $\log N({\rm He})/N({\rm H}) = -1.44$, is in excellent agreement with that obtained by Burleigh et al. (2001), $T_{\rm eff} = 33,000$ K and $\log N({\rm He})/N({\rm H}) = -1.5$ (their value of $\log g$ is not given). The problem mentioned by these authors with the HeII $\lambda$4686 predicted by their models is not observed here, however, even though this particular line is included in our model calculations. The fits to the hydrogen Balmer lines are qualitatively similar between the homogeneous and stratified models: the low Balmer lines (H$\beta$ to H$\delta$) are predicted too strong while the higher members are too weak. The homogeneous model yields a satisfactory fit for the HeI lines $\lambda\lambda$4026, 4713, and 5015, but a poor fit to the remaining helium lines. The fit with the stratified model is considerably worse.

On the other hand, the DA+DB solution provides an excellent fit to the Balmer and

neutral helium lines simultaneously. All observed features are reproduced in detail and this is clearly the only viable solution for PG 1115+166. The effective temperatures determined for both the DA and the DB components are significantly lower than the values achieved under the assumption of a single object with a homogeneous or stratified composition. This is a direct consequence of the hydrogen lines being diluted by the continuum flux of the DB star (see below); the Balmer lines are weakened, and the effective temperature of the model needs to be increased to match the observed line profiles.

The surface gravities of both components of the system are almost identical, $\log g \sim 8.15$, which corresponds to a mass of $\sim 0.7\ M_\odot$ using the evolutionary models described above. The white dwarf cooling ages inferred for the DA and DB stars are respectively $6.0 \times 10^7$ and $2.2 \times 10^8$ years. Since both stars have roughly the same radius, the contribution of each component to the total luminosity is only a function of the effective temperature. Since the DB star is significantly cooler than the DA component, the former will contribute less to the combined luminosity of the system. This is illustrated more quantitatively in Figure 3 where the contribution of each component to the total flux is depicted. Also shown is the multichannel *ugvr* photometry taken from Green et al. (1986, $v = 15.14$, $u - v = 0.15$, $g - v = -0.14$, $g - r = -0.51$), which is in good agreement with our adopted solution, with the exception of the $u$ magnitude; multichannel $u$ magnitudes were sometimes compromised by the atmospheric dispersion, the finite size of the entrance aperture, and the drift of the target away from the aperture center during the exposure. While the flux in the ultraviolet is completely dominated by the DA component, there is a more significant contribution of the DB star in the optical regions of the energy distribution. In particular, the cores of the lower Balmer lines are filled in by the continuum flux of the DB star, resulting in the poor fits of the homogeneous and stratified solutions displayed in Figure 2 and discussed above.

Finally, Burleigh et al. (2001) have reported radial velocity variations in PG 1115+166 from H$\alpha$ measurements (see their Fig. 2), with possible HeI $\lambda$6678 moving in anti-phase with the hydrogen line, in agreement with a DA+DB interpretation. No orbital period has yet been reported.

## 5. Discussion

Our analysis has shown conclusively that the simultaneous presence of hydrogen and helium in the spectrum of PG 1115+166 is a simple result of an unresolved binary system composed of a DA white dwarf and a DB star. Both components of the PG 1115+166 system lie well below the cool edge of the DB gap, and as such, this DAB "system" cannot contribute to our understanding of the nature of the DB gap. Two other DAB stars,

MCT 0128−3846 and MCT 0453−2933 shown in Figure 1, are similar DA + DB (or DBA) unresolved composite systems, rather than single objects with mixed hydrogen and helium compositions.

Additional DAB stars include HS 0209+0832, a $T_{\rm eff} \sim 35,000$ K white dwarf that has been recently observed with HST and analyzed by Wolff et al. (2000). The authors conclude that the hydrogen and helium lines, as well as numerous metallic features, are all compatible with a homogeneously mixed composition, and that the object is probably in the process of accreting matter from the interstellar medium. If this is the case, HS 0209+0832 is a transient phenomenon, and is not connected to the DB gap either. Its temperature within the DB gap is thus purely coincidental.

The case of G104−27 reported by Holberg et al. (1990), with a temperature of $T_{\rm eff} = 26,000$ K, is also peculiar. Their spectrum shows a weak HeI $\lambda$4471 feature, and possible $\lambda$5015. However, subsequent observations of this object, including 7 independent spectra collected over the years by one of us (PB), reveal a featureless spectrum near the $\lambda$4471 region. This particular spectroscopic feature may of course be variable, as is the case for HS 0209+0832 (Edelmann et al. 2001). Such variations could be expected if G104−27 and HS 0209−0832 accrete from an inhomogeneous interstellar medium, or if the distribution of helium on the stellar surface is inhomogeneous, as discussed by Edelmann et al. (2001).

Finally, there is GD 323, the prototype of DAB stars. Liebert et al. (1984) showed that the combined ultraviolet and optical spectrophotometry of this star could not be reproduced with a homogeneously mixed hydrogen and helium composition, and suggested that a fit with a stratified composition be attempted. This idea was explored more quantitatively by Koester et al. (1994) who confirmed that the most promising explanation to account for the observed line profiles was a stratified atmosphere. Their estimated temperature of $T_{\rm eff} = 28,750$ K places GD 323 just below the cool end of the empirical DB gap. However, even their stratified solution does not reproduce the optical spectrum very well, at least not at the level of our best fit for PG 1115+166 shown in Figure 1, and inconsistent values of the hydrogen layer mass are derived from the optical and ultraviolet spectra.

All in all, there seems to be no such objects as "DAB stars transiting the DB gap", as sought by Burleigh et al. (2001); we mention also that no additional DAB spectrum has been identified in our PG luminosity function sample. This is perhaps not surprising, however. Indeed, if the scenario proposed to explain the DB gap is correct, by definition we should not observe any helium-rich objects crossing the DB gap. Stars with mixed hydrogen and helium compositions must be searched either slightly above the hot end of the DB gap ($T_{\rm eff} \gtrsim 45,000$ K) or slightly below the cool end ($T_{\rm eff} \lesssim 30,000$ K). Interestingly enough, such stars have probably already been identified. PG 1305−017 analyzed by Bergeron et al.

(1994), with an estimated temperature of $T_{\rm eff} = 44,400$ K, is the perfect example of a hybrid white dwarf with strong hydrogen and helium lines – a DAO star in this case – that can be successfully explained in terms of a stratified chemical composition (see Fig. 8 of Bergeron et al.). This object corresponds precisely to our expectation of a DO star turning into a DA star near the hot end of the DB gap, i.e. a thin hydrogen atmosphere in diffusive equilibrium on top of a helium envelope. Similarly, at the cool end of the DB gap, the reappearance of helium-rich atmosphere white dwarfs near 30,000 K is explained in terms of the dilution of this thin hydrogen atmosphere with the more massive underlying helium convection zone. It is clear that DA white dwarfs caught in the process of being convectively diluted will have a complex chemical stratification that will not be homogeneous nor stratified. GD 323 with a temperature slightly below the cool edge of the DB gap might be such an exotic object. Hence, objects that could support the DO to DA and DA to DB transition scenarios do exist, but they should not be looked for within the DB gap itself. This interpretation is at least currently supported by observations.

One possible scenario for the origin of Type Ia Supernovae is the double degenerate model in which two white dwarfs with a total mass exceeding the Chandrasekhar limit are assumed to coalesce (Webbink 1984; Iben & Tutukov 1984). In order for the system to merge within a Hubble time, however, the orbital period must be less than $\sim 10$ hours. Since the total mass of the PG 1115+166 system ($M \sim 1.4\ M_\odot$) is close to the Chandrasekhar limit, a precise measurement of its orbital period would establish whether PG 1115+166 represents a likely supernova candidate.

This work was supported in part by the NSERC Canada, by the Fund FCAR (Québec), and by the NSF grant AST 92-27961.

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Fig. 1.— Comparison of our optical spectrum of the DAB star PG 1115+166 with those of MCT 0453−2933 and MCT 0128−3846, two additional DAB stars that have been interpreted by Wesemael et al. (1994) as unresolved composite systems consisting of a DA white dwarf and a DB or DBA companion. The spectra are normalized at 4400 Å and are shifted vertically by 0.5 for clarity.

Fig. 2.— Our best fits to the optical spectrum of PG 1115+166 using homogeneous, stratified, and composite DA+DB models. The atmospheric parameters for each solution are given in the figure. Both the observed and theoretical spectra are normalized to a continuum set to unity. The top spectra are shifted by a factor of 0.4 from each other for clarity. Clearly, the DA+DB solution provides the best fit to the overall spectrum.

Fig. 3.— Relative energy distributions for our best DA+DB fit obtained in Figure 2. The thin lines show the individual contributions of the DA and DB components, properly weighted by their respective radius, while the thick line corresponds to the total monochromatic flux of the composite system. The dots indicate the multichannel *ugvr* photometry normalized at the *v* magnitude to match the predicted energy distribution.

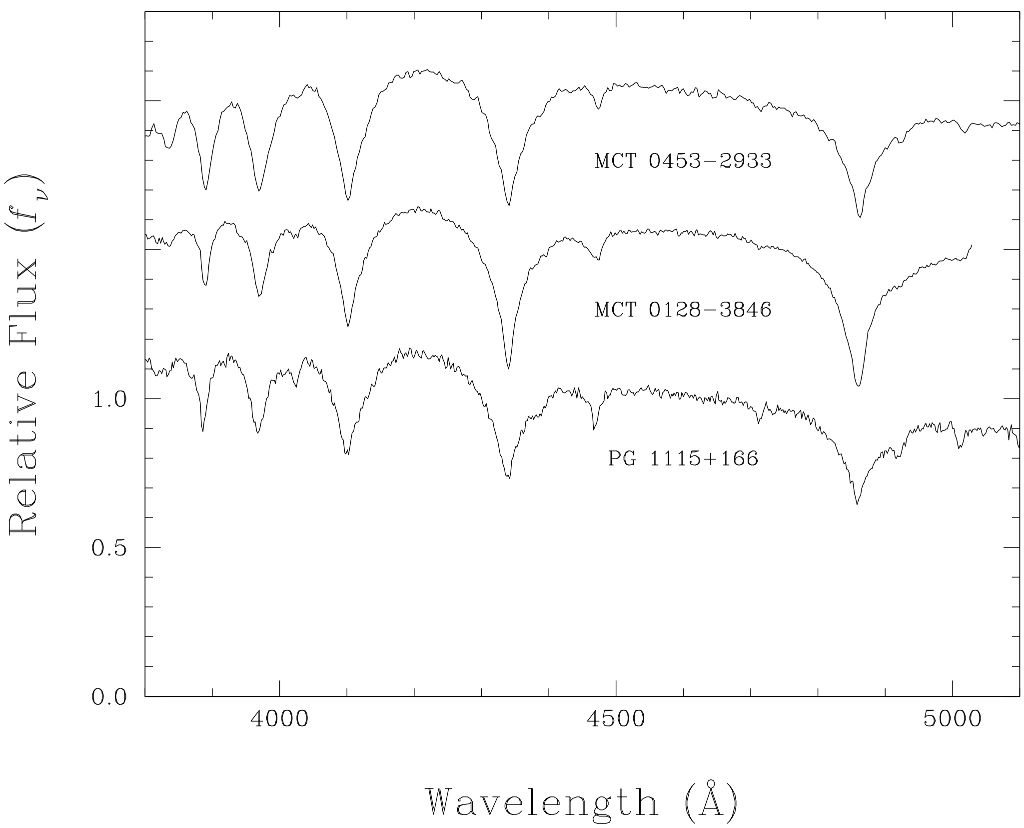
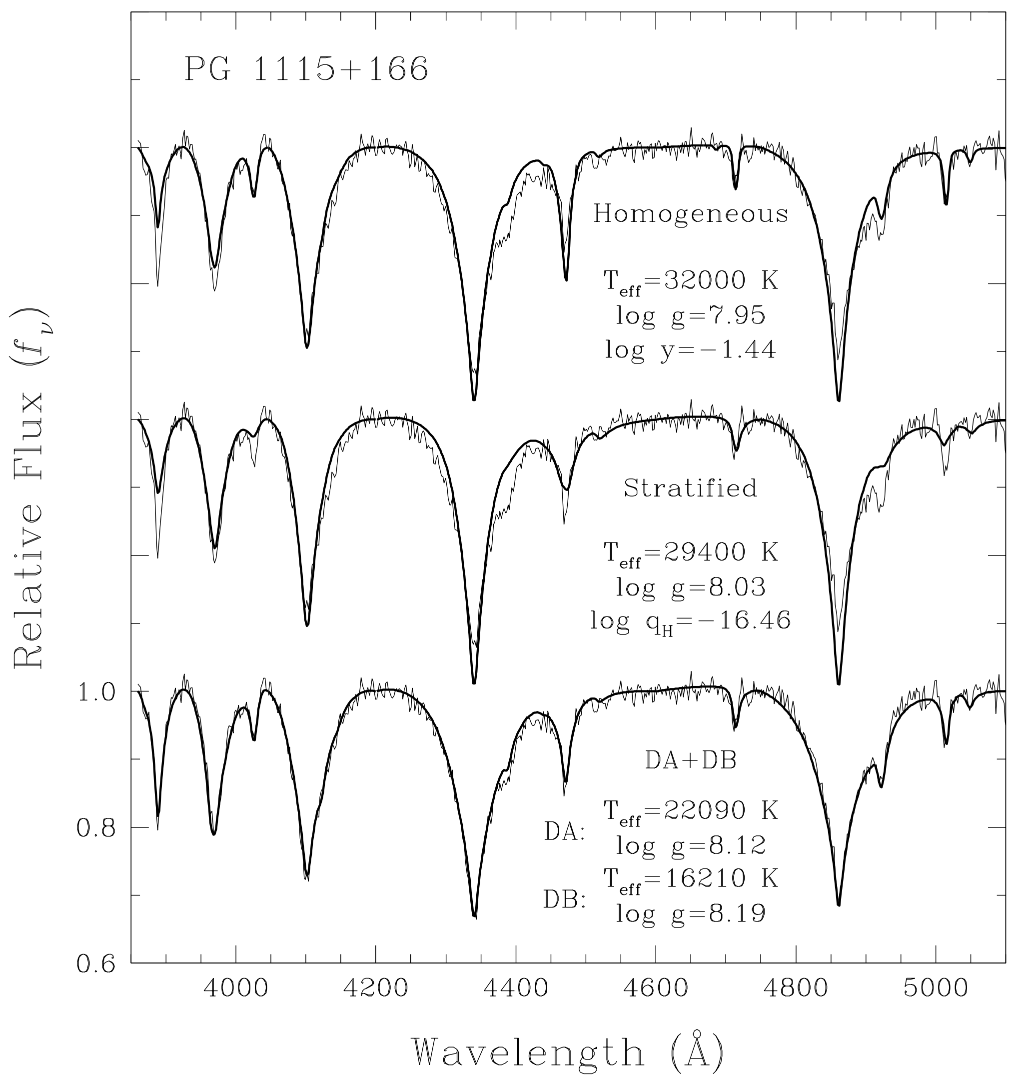

MCT 0453−2933
MCT 0128−3846
PG 1115+166
Relative Flux ($f_\nu$)
0.0
0.5
1.0
4000
4500
5000
Wavelength (Å)

Figure 1



PG 1115+166
Homogeneous
$T_{eff}$=32000 K
log g=7.95
log y=−1.44
Stratified
$T_{eff}$=29400 K
log g=8.03
log $q_H$=−16.46
DA+DB
DA: $T_{eff}$=22090 K
log g=8.12
DB: $T_{eff}$=16210 K
log g=8.19
1.0
0.8
0.6
4000
4200
4400
4600
4800
5000
Relative Flux ($f_\nu$)
Wavelength (Å)


Figure 2

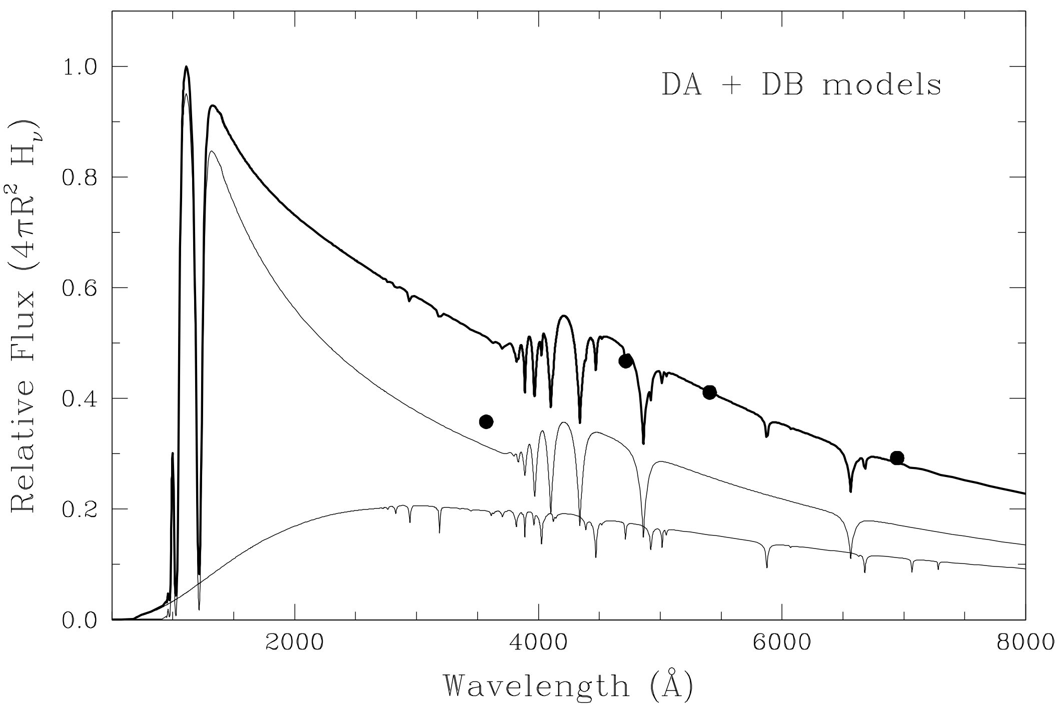

DA + DB models
Relative Flux ($4\pi R^2$ $H_\nu$)
0.0
0.2
0.4
0.6
0.8
1.0
2000
4000
6000
8000
Wavelength (Å)

Figure 3